



# **Extravehicular Mobility Unit Training Suit Symptom Study Report**

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## **Acknowledgments**

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## Acronyms

APFR	articulating portable foot restraint
ASCAN	astronaut candidate
ASCR	Astronaut Strength, Conditioning, and Rehabilitation [Team]
BRT	body restraint tether
BSI	boot sizing insert
EMU	extravehicular mobility unit
EVA	extravehicular activity
g	gravity
HUT	hard upper torso
ISS	International Space Station
JSC	Johnson Space Center
LCVG	liquid cooling and ventilation garment
LSS	life support subsystem
NBL	Neutral Buoyancy Laboratory
PFR	portable foot restraint
PGT	pistol grip tool
SAFER	simplified aid for EVA rescue
USA	United Space Alliance

## Abstract

**Background:** The purpose of this study was to characterize the symptoms and injuries experienced by NASA astronauts during their extravehicular activity spacesuit training at the Neutral Buoyancy Laboratory. We identified the frequency and incidence rates of symptoms by each general body location and characterized mechanisms of injury and effective countermeasures. Based on these findings a comprehensive list of recommendations was made to improve training, test preparation, and current spacesuit components, and to design the next-generation spacesuit. **Methods:** At completion of each test event a comprehensive questionnaire was produced that documented suit symptom comments, identified mechanisms of injury, and recommended countermeasures. Comments were analyzed by each general and specific anatomic location, severity, causal mechanism, and recommended countermeasure. **Results:** Of the 770 test events studied, 352 reported suit symptom comments (45.7%). Of those symptoms 166 were in hands (47.16%), 73 were in shoulders (20.7%), and 40 were in feet (11.4%). Others ranged from 6.0% to 0.28%, respectively, from the legs, arms, neck, trunk, groin, and head. The major causal mechanisms for the hands included hard fingertip contacts associated with fingernail delamination, in the shoulders hard contact with suit components and strain mechanisms, and in the feet with hard contact in boots. The reported severity of symptoms was highest in the shoulders 1.86/5, with 1.3/5 in the hands, and 1.66/5 in the feet and ranged from 1.65/5 to 0.4/5 for the arms, legs, neck, and trunk, respectively. **Conclusion:** Most extravehicular mobility unit suit symptoms were mild, self-limited, and controlled by available countermeasures. Some represented the potential for significant injury with short- and long-term consequences regarding astronaut health and interference with mission objectives. The location of symptoms and injuries that were most clinically significant was in the hands, shoulders, and feet. Correction of suit symptom issues will require a multidisciplinary approach to improve prevention, early medical intervention, astronaut training, test planning, and suit engineering.

## 1 Introduction

### 1.1 Background

Employees of the Johnson Space Center (JSC) Medical Operations and Occupational Medicine/Manned Test Support recognized early in 2002 that there was an apparent increased incidence of a variety of complaints associated with extravehicular activity (EVA) training at the Neutral Buoyancy Laboratory (NBL). Many of these had apparently been unreported or had not been completely captured by the Flight Medicine Clinic and the Astronaut Strength Conditioning and Rehabilitation records. These complaints and injuries have probably always been occurring at a low incidence. However, the unprecedented increase in EVA training to support construction and maintenance of the International Space Station (ISS) may have significantly accentuated this problem. It appeared that most of these complaints were minor and self-limited in nature. However, it was suspected that some of these represent injuries that could persist and thereby impact astronaut health and possibly mission objectives. Up to this time no data had been developed to quantify and characterize these complaints.

In 2000 Dr. Michael Gernhardt, astronaut and researcher, suggested that a study be conducted to evaluate extravehicular mobility unit (EMU)-related symptoms as a tool to distinguish these from possible decompression sickness symptoms following EVA on orbit. In early 2002 at the request of Dr. David Williams, Dr. Craig Fischer, and Dr. Charles Ross, the author was asked to develop a new function as the EMU Medical Monitor. One of the products of that function was the proposal to study EMU suit symptoms in NBL training, and to report the findings/recommendations to team members in the Space Medicine and EVA communities. This study was initiated on July 19, 2002.

## **1.2 Training, Facilities, Equipment, and Environment**

### **1.2.1 Training**

NASA astronaut and International Partners neutral buoyancy EVA EMU training is conducted at the JSC NBL. EVA mission training is provided for assigned missions scheduled on orbit from the Space Shuttle and ISS. The training-to-flight ratio is approximately 10–12 hours of training for each hour of EVA planned on orbit. Therefore, a flight in which three EVAs consisting of seven hours each are planned would typically require 210–250 hours of in-water, mission-specific training. Mission training flows usually start approximately one year before the scheduled space flight.

The primary source of EMU EVA training is from designated materials and instructors of the EVA Robotics and Crew and Thermal Systems Division of the Mission Operations Directorate.

Astronaut EMU training is provided during astronaut candidate (ASCAN) training using equipment familiarization in the classroom, a workbook, computer-based training, and equipment demonstrations. Initial EMU operations training is conducted at the Systems Integration Facility. This includes suit-up, pressurization, and display and controls module (DCM) demonstrations. Didactic and demonstration training for EVA tools precedes NBL in-water training for ASCAN and EVA skills training flows. Tasks, airlock, EVA procedures, mock up, and translation path training are provided informally in a briefing/debriefing format associated with NBL training test events.

In-water EMU evaluation and training phases at the NBL consist of four training flow types:

- ASCAN suit qualification/task familiarization and evaluation: This usually consists of four training test events of three to four hours each.
- EVA skills training: These test events usually consist of eight to 12 sessions consisting of four to six hours each.
- Contingency EVA training: EVA astronauts receive NBL EMU training in contingency operations including the payload bay door, Remote Manipulator System, airlock hatch, Ku- band antenna system, payload retention latches, orbital docking system, and the Thermal Protection System.
- Mission training for assigned crew: Total NBL training time depends on the number of planned EVAs, and the complexity of development and training required. To date, the

number of ISS/Hubble EVAs have ranged from one to five per mission, with an average training ratio of 11.6:1 (hours of EMU training in the NBL per hour of EVA).

### 1.2.2 Facilities

The NBL, which is located in the Sonny Carter Training Facility (fig. 1-1) consists of a 6.2-million-gallon water tank that is 202 feet long, 102 feet wide, and 40 feet deep. It provides controlled neutral buoyancy operations to simulate weightless conditions experienced by Space Shuttle and Space Station crews and payloads during space flights. The facility water tank uses full-size mockups of space flight equipment including the Space Shuttle cargo bay, the ISS, functioning remote manipulator arms, orbital replacement units, and associated flight hardware.

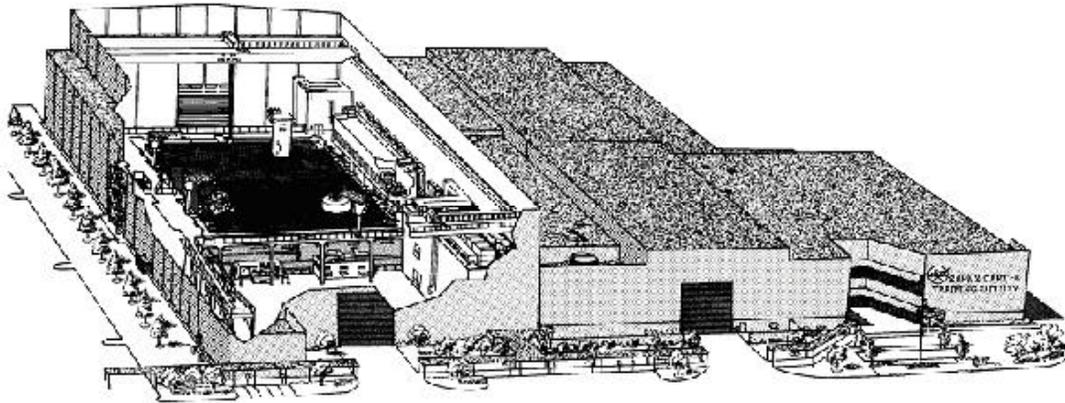


Figure 1-1. Sonny Carter Training Facility.

### 1.2.3 Equipment

The EMU spacesuit was developed for the U.S. space program under a NASA contract with Hamilton Sundstrand. It was designed to provide the astronaut with life support and the mobile pressure enclosure necessary to perform EVAs in Earth orbit. In addition, some EVAs conducted on the ISS use the Russian Orlan spacesuit. Orlan training is conducted at the Hydrolab in Star City, Russia. Astronauts and cosmonauts are trained in each configuration as required.

The spacesuit assembly used at the NBL is categorized as Class III, certified for training only. The EMU is maintained and supported under contract with United Space Alliance (USA). The spacesuit assembly consists of the EMU, DCM mockup, life support subsystem (LSS) mockup, and simplified aid for EVA rescue (SAFER) mockup. EMU components are sized and built for each suited subject by a modular assembly method that has an approximate weight of 180 lbs. EMU soft goods generally have 13 layers of materials. Attached tools and tethers are configured according to each specific EVA tasking.

### 1.2.3.1 Class III EMU description

The EMU (fig. 1-2) is a modular design that consists of nine major components. These are the:

- Liquid cooling and ventilation garment (LCVG), a conformal garment that contains tubing that is woven through it. Cooling water is circulated through the tubing at various flow rates to maintain temperature control at varying workloads. It also contains ducts and vent tubes that collect returning breathing gas from the arms and legs. The thermal comfort undergarment is worn under the LCVGs to protect the skin, absorb moisture, and provide comfort.
- Communications carrier assembly, an aviator-like cap that contains earphones and microphones.
- Hard upper torso (HUT), which consists of a fiberglass shell that connects to the arm assemblies, helmet, and lower torso assembly. Two HUT designs are in use at the NBL. The older design used in training only is the pivoted HUT. This contains a shoulder gimbal with a two-point pivot to facilitate donning and doffing. The enhanced, or planar, HUT design is currently used for training and space flight. It has planar scye bearing openings that attach to each arm opening.
- In-suit drink bag/disposable in-suit drink bag, a sealed flexible container with drink valve that holds either 21 or 32 oz of drinking water. It is attached with Velcro to the right inner front wall of the HUT.
- Arm assemblies, which consist of flexible anthropomorphic pressure vessels to which the gloves are attached. They contain an area of plicated material, the elbow convolute, to assist in elbow flexion.
- Glove assemblies, which attach to each arm assembly. They are designed to allow the astronaut to have the best possible dexterity, tactility, and precision.
- Lower torso assembly, a flexible anthropomorphic pressure vessel that encompasses the waist, lower torso, legs, and feet. Each leg contains an area of plicated material, the knee convolute, to reduce resistance in knee flexion.
- Helmet, which consists of a detachable, transparent, hard pressure vessel that encompasses the head. A Valsalva device may be installed to assist the suited subject in clearing ears, and a Fresnel lens may be installed to refract for near vision if required.
- Ancillary support equipment, which includes the electrical harness; a maximum absorbency garment, a waste containment garment; the primary life support subsystem mockup; the DCM mockup; the SAFER mockup; a cuff checklist; and mirrors, tools and tethers.

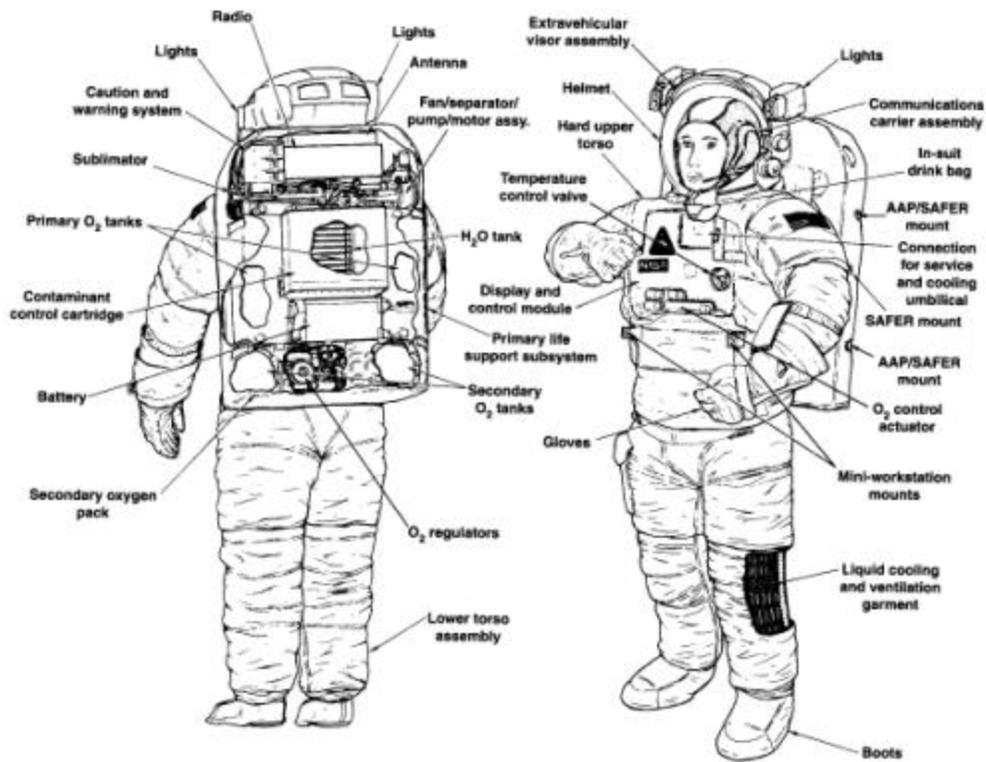


Figure 1-2. EMU from Hamilton Sundstrand.

### 1.2.3.2 Tools

EVA astronauts usually handle from 70 to 110 tools, tethers, and associated equipment for a typical EVA. EVA tools are maintained and supported under contract with USA. Several tools/tethers are deployed from a modular mini-workstation that is mounted on the front of the EMU. Other tools are stored in toolboxes on the Orbiter/ISS or are carried out to the worksite through the airlock. Tools may also be deployed from a tool stanchion. Of special concern at the NBL are the so-called “heavy tools,” (fig. 1-3) many of which are heavier than 10 lbs and may be a source of musculoskeletal stress—particularly to upper extremity structures such as hands, elbows, and shoulders. Weight limits for arm extended heavy tool lifting are 9.7 lbs, 5-percentile female astronaut, to 11.9 lbs, 95-percentile male astronaut. In addition, operation of some heavy tools also creates or requires a torque force, with the potential for further aggravating stress mechanisms of the upper extremities. Furthermore, some stressors result from requirements to work in confined spaces or other precarious body positions. Heavy tools include the three point and centerline latch tools, pistol grip tool (PGT) and attachments, and the orbital docking system clamp. Tools that require a torque force include the PGT, the drive ratchet, and wrenches.



Figure 1-3. Heavy EVA tools.

### 1.2.4 Environment

The training environment is essentially hard-hat diving to a maximum depth of 40 feet. The suit is pressurized above ambient to 4.3 psi, or approximately 10 feet seawater pressure. Unlike the EMUs used in space, Class III suits are tethered to an umbilical, which delivers breathing gas (Nitrox/54% nitrogen, 46% oxygen), cooling water, and communications. This system is monitored and controlled by the NBL environmental control system. Neutral buoyancy weigh-outs distribute various weights on several locations of the EMU to allow the astronauts to float neutrally buoyant at any body position and depth in the water column. The effects of changing water pressure, fluid resistance, and Earth's gravity (g) are experienced in the NBL, which make this training environment significantly different from conditions of weightlessness of space.

### 1.3 Scope

This study was designed to identify and quantify EMU suit related symptoms experienced by astronauts in training at the NBL. It characterizes these by anatomic location, severity, and attributed causes.

It was conducted from July 19, 2002, to January 16, 2004, at the NBL located at the Sonny Carter Training Facility of JSC. The study was completed when it was determined that adequate data were collected to meet study goals.

The investigation was coordinated, conducted and supported by the Kelsey-Seybold Clinic (NASA contractor) and the Space Medicine and Health Care Systems Office of the Space and Life Sciences Directorate.

## **2 Philosophy**

The most effective means of collecting complete and accurate comments from astronauts regarding symptoms experienced in the EMU was to acquire the comments at the completion of each NBL test event. The data were collected by a Flight Surgeon who is well known and trusted by the astronauts and who is assigned to the NBL. The data were then immediately recorded in the study computer-based format.

## **3 Approach**

### **3.1 Objectives**

The overall objective of this study was to determine the frequency, nature and severity of NBL EMU training-related suit symptoms. Secondary objectives were to characterize these by attributed causal mechanisms, and then to develop a comprehensive series of recommendations to prevent these in the future. The anticipated outcome is to control the mechanisms of injury and, thus, improve astronaut health and the quality of NBL EVA training.

### **3.2 Questions**

This investigation is designed to answer the following questions:

- What is the frequency of EMU suit-related signs, symptoms, or injuries?
- What is the frequency of complaints by location, characteristics, and severity?
- What causal mechanisms can be identified?
- Can effective countermeasures be introduced to prevent identified problems?
- What trends can be identified to develop recommendations to the space medicine, the suit engineering, and the astronaut training communities?

For purposes of this study, the terms “sign, symptom, and injury” are defined as:

- Sign or symptom is self-limited; it does not require medical care and does not restrict function.
- An injury, such as a cut, a fracture, a sprain, an amputation, etc., results from a work-related event or from a single instantaneous exposure in the work environment.

The Severity Scale was characterized as follows:

- 0 – No pain
- 1 – Very mild pain
- 2 – Mild pain
- 3 – Moderate pain
- 4 – Moderately severe pain
- 5 – Severe pain

## **4 Contributing Responsibilities**

### **4.1 Test Team Personnel**

The following study team members were responsible for study development, planning, data collection, and analysis:

Test Sponsor	Charles Ross, DO, MPH (NASA / SD 3)
Principal Investigator	Samuel Strauss, DO, MPH (KS / SD 37)
Backup Flight Surgeon	Daniel Fitzpatrick, DO, MPH (KS / SD 37)

### **4.2 Support Personnel**

The following person was responsible for providing support:

Data Development and Analysis	Ralph Krog, JD (NSBRI / SD 6)
-------------------------------	-------------------------------

## **5 Description**

The research design is a Prospective Observational Study. The study population consisted of active NASA astronauts, including participating International Partners, who received training in the EMU at the NBL. Participation was voluntary; verbal informed consent was given by each subject. Subjects may have withdrawn at any time. No intervention was involved outside of requesting comments and observing findings following normal training. The study plan was reviewed and approved by the JSC Committee for the Protection of Human Subjects by Expedited Review valid to January 31, 2004.

## **6 Evaluation Method**

### **6.1 Sample Size**

Because the frequency of some of the variables was found to be low, data collection continued until the required sample size was achieved. The sample size collected was on the order of > 700 Suit Symptom Questionnaires.

### **6.2 Data Collection**

A qualified Kelsey-Seybold Flight Surgeon collected data at the conclusion of NBL test events. Each subject was confidentially interviewed, and the results were recorded on the Suit Symptom Questionnaire. When appropriate, the accompanying photo-documentation was correlated with Suit Symptom Questionnaire data.

### **6.3 Data Entry**

Data entry was completed as soon as possible after collection and recorded on a Suit Symptom Questionnaire Microsoft Excel form according to questionnaire guidelines. The data were spontaneously populated onto an associated Microsoft Access table schema that served as the relational version to be used in analysis.

### **6.4 Records Confidentiality/Security**

Since this database contains names, dates, attributable symptoms and diagnoses, it was handled as medical information, in accordance with the Privacy Act of 1974, and Maintaining the Privacy of Biomedical Research Data (JMI 1382.5A). The Principal Investigator, who is a licensed physician, controls the data. Computerized data will remain password protected on a NASA computer. CD-ROM and hard copy data are secured in a locked file cabinet accompanied by a Privacy Act Statement. A Medical Information Specialist of the Space Medicine and Health Care Systems Office of Medical Informatics provided support in data development and analysis. Similarly all data remain password protected or secured in a locked file cabinet accompanied by a Privacy Act Statement. All reported data are presented in a non-attributable format. Photo documentation used for briefings or publications is also in a non-attributable format. Consent was obtained from subjects before photo-documentation was used in this manner.

### **6.5 Data Analysis**

A Microsoft Access table schema was the relational version of the collected data from the Microsoft Excel Suit Symptom Questionnaire. This was installed in the Medical Informatics framework for NASA Attributable Medical Databases before it was analyzed using Microsoft SQL Server. Data analysis consisted of calculating the frequency rates from questionnaires with

positive responses to the total number of questionnaires. Analysis also measured and compared frequency rates of complaints by location, characteristics, severity, and causal mechanisms. Incidence rates by suited subjects were also calculated. Repeated similar complaints by the same subject were reviewed for chronicity. Any trend in the reporting of similar complaints by the same suited subject was used to evaluate the possible benefit of countermeasures.

## 6.6 Potential Biases

Anticipated potential biases included underreporting by study subjects, delay in the onset of complaint symptoms, variations in exposure types and times, variations in astronaut gender, age, conditioning, body type, and experience, and differences in tasks/equipment (HUT/glove designs and tools used). Another bias was due to the correction of problems as they were identified.

# 7 Results

## 7.1 Summary of Data

At the completion of 18 months' study, 770 suited test events were evaluated. This represented 86 astronaut-suited subjects from July 19, 2002, through January 18, 2004. The following is a summary of findings:

- Study population = 86
- Total test events = 770
- Number of reported symptoms = 352

### 7.1.1 Frequency of test events with symptoms

- The number of **test events** with any symptoms = 190 (68 + 122 = 190)
- The number of **test events** with one symptom = 68
- The number of **test events** with more than one symptom = 122
- Test events with any **symptoms** : **total test events** is  $190/770 = 24.6\%$

### 7.1.2 Frequency of reported symptoms

- The total number of **symptoms** in the "one symptom" group = 68
- The total number of **symptoms** in the "more than one symptom" group = 284
- The total number of **symptoms**  $68 + 284 = 352$
- **Total symptoms** : **total test events** is  $352/770 = 45.7\%$

## 7.2 Frequency of Symptoms by Location

The frequency of symptoms distribution (location vs. total symptoms) is shown in Table 7-1. A chart of this appears immediately after, in figure 7-1.

Table 7-1. Frequency of Symptoms Distribution (Location vs. Total Symptoms)

Location	Right (%)	Left (%)	Nonlateral (%)	Total %
Hands	89/352 (25.28)	77/352 (21.88)		47.16
Shoulders	45/352 (12.78)	28/352 (7.95)		20.73
Feet	24/352 (6.82)	16/352 (4.55)		11.37
Arms	16/352 (4.55)	5/352 (1.42)		5.97
Legs	13/352 (3.69)	7/352 (1.99)		5.68
Neck			20/352 (5.68)	5.68
Trunk			10/352 (2.84)	2.84
Groin			1/352 (0.28)	0.28
Head			1/352 (0.28)	0.28

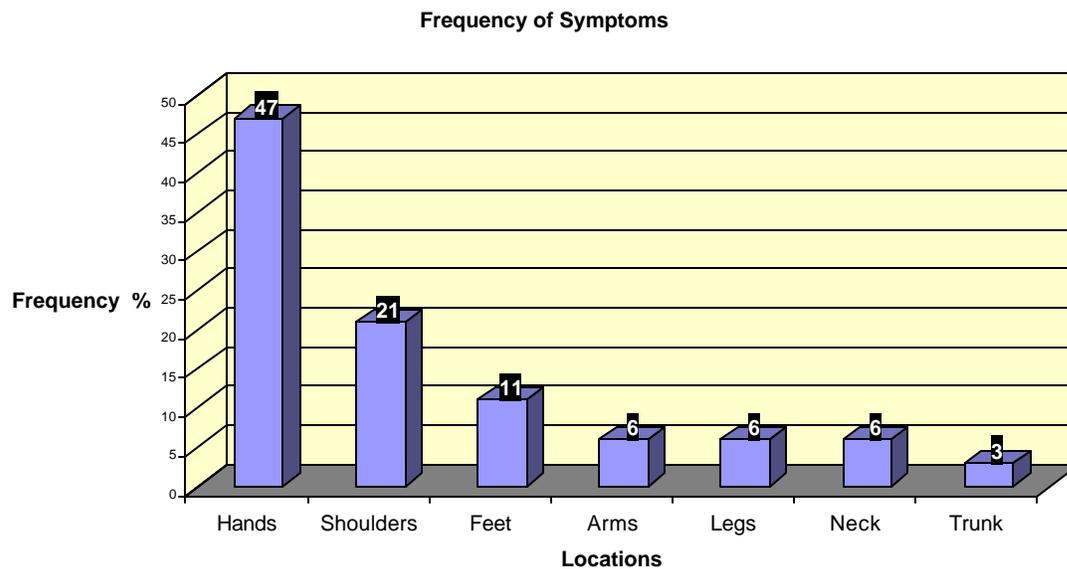


Figure 7-1. Frequency of symptoms distribution (location vs. total symptoms).

## 7.3 Incidence Rates – Subjects by Location

Incidence rate is the ratio of subjects with symptoms to subjects at risk (expressed as %).

- Incidence rate of subjects with symptoms  $60/86 = 70\%$
- Incidence rate of subjects with one symptom  $13/86 = 15\%$
- Incidence rate of subjects with two or more symptoms  $47/86 = 55\%$

Of the 60 subjects with symptoms, there were a total of 194 location complaints (subject counts) distributed as shown in Table 7-2 and charted in figure 7-2.

Table 7-2. Incidence of Symptoms Distribution (Subject Counts) by Location

Location	Right	Left	Non-lateral	Total	Incidence Rate (%)
Hands	33	33		66	$66/194 = 34$
Shoulders	21	18		39	$39/194 = 20$
Feet	19	14		33	$33/194 = 17$
Neck			18	18	$18/194 = 9$
Arms	10	5		15	$15/194 = 8$
Legs	8	6		14	$14/194 = 7$
Trunk			7	7	$7/194 = 4$
Groin			1	1	$1/194 = 0.5$
Head			1	1	$1/194 = 0.5$

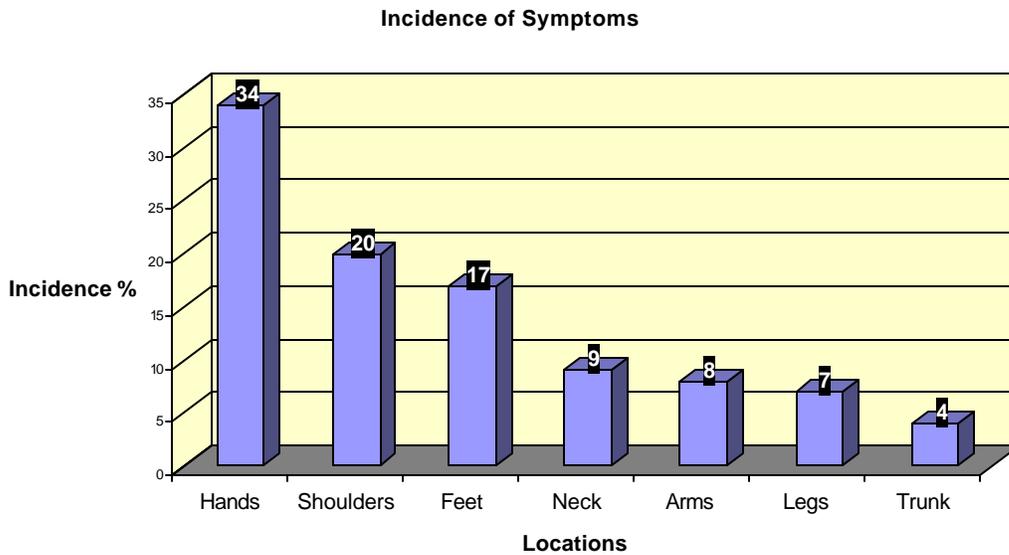


Figure 7-2. Incidence of symptoms by location distribution.

## 7.4 Characteristics, Average Severity, and Attributed Causes

### 7.4.1 Hands

#### *Frequency 47.16%*

These primarily involve fingernail delamination (onycholysis) attributed to axial loading and moisture in comfort gloves. Fingertip pain was attributed to hard contact to the fingertips with extended reaching and forceful grasping. Other assorted complaints included superficial abrasions, contusions, and two peripheral nerve impingements that were attributed to glove fit and unprotected contacts. Some of the astronauts complained of generalized hand fatigue following several hours of repeated and forceful grasping.

#### *Average Severity 1.13/5 (Scale of 0 – 5)*

Causes (distribution by specific location) of hand complaints, including fingernail delamination (fig. 7-3), are:

- Fingertips / nails contact – 55%
- Other glove contact – 35%
- Fatigue – 8%

During this study period 18 astronauts were followed for hand complaints. Thirteen of these were for fingernail delamination.



Figure 7-3. Example of fingernail delamination.

### 7.4.2 Shoulders

#### *Frequency 20.73%*

Half of these were comments attributed to hard contact between the shoulders and the HUT. They were worse with heads down and shoulders/arms abducted. The most common symptoms were attributed to unprotected contact with the planar HUT, especially at the scye joint.

Shoulder rotator cuff stress and strain injuries were also reported, particularly after the shoulder joints were used in compromised positions exacerbated by the inherent design of the planar HUT. Compromised body positions included heads down and rotation laterally and supine especially associated with reaching into extension such as to deploy a swing arm or body restraint tether (BRT) (fig. 7-4). In the planar HUT, shoulders are forced into internal rotation, there is often a mismatch between the HUT opening and the functional range of motion of the shoulders, and there is a limited safe work envelope.

***Average Severity 1.86/5 (Scale of 0 – 5)***

Causes of shoulder complaint are:

- HUT contact – 47%
- Strain, sprain, tear, overuse, and impingement injuries – 46%
- Harness contact – 7%

During this study period 13 astronauts were referred and followed for shoulder complaints. Two were referred for surgical intervention.

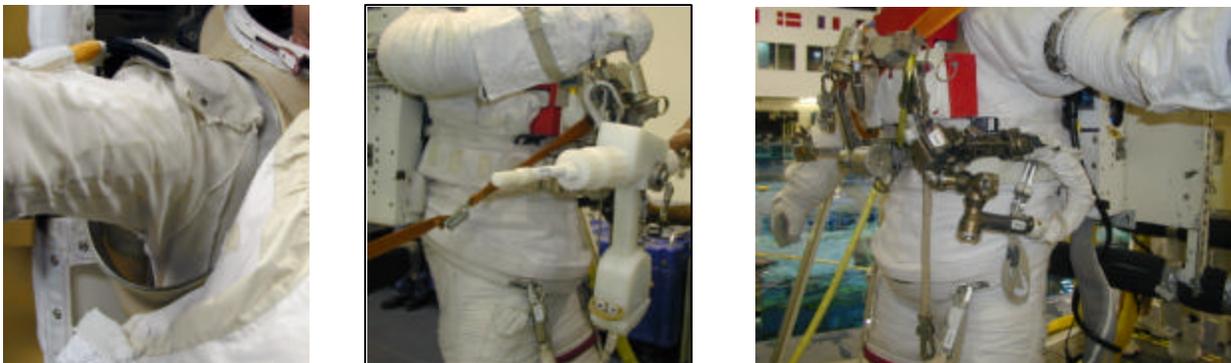


Figure 7-4. Planar HUT, swing arm, BRT.

### **7.4.3 Feet**

***Frequency 11.37%***

Most of the problems with feet were compression complaints on the tops of the feet and distal toes associated with problems with the boot fit. A common comment was that boot sizing inserts (BSIs) and other inserts were not comfortable or became displaced during the test event (fig. 7-5). It was noted that key areas of the foot were not protected, and that there is no foot arch support built into the current BSI design. BSIs did not adequately protect the feet from hard contacts including from the 1g effect on the front of toes, hard contact on the tops of feet while in the portable foot restraints (PFRs)/articulating portable foot restraints (APFRs), and bladder folds.

***Average Severity 1.66/5 (Scale of 0 – 5)***

Causes of foot complaint are:

- Boot contact causing dorsal foot pain – 60%
- Hard contact with the front of the boot causing toe pain – 28%
- Poor protection and lack of support causing heel and arch pain – 12%



Figure 7-5. BSIIs, feet.

#### **7.4.4 Arms**

***Frequency 5.97%***

Most of the problems with arms were attributed to hard contact and rubbing by the soft goods to the elbows. Strains were due to elbow overuse mechanisms, manifest mostly as lateral or medial epicondylitis.

***Average Severity 1.65/5 (Scale of 0 – 5)***

Causes of arm complaint are:

- Contact causing abrasions and contusions – 65%
- Strains – 35%

During this study period three astronauts were referred and followed for elbow strain complaints.

#### **7.4.5 Legs**

***Frequency 5.68%***

Problems with the legs were attributed to contact in the knees, especially while flexed and bearing most of the body weight. One ankle complaint was due to hard contact at the dorsal ankle from the boot.

***Average Severity 1.56/5 (Scale of 0 – 5)***

Causes of leg complaint are:

- Knee contact – 95%
- Ankle contact – 5%

**7.4.6 Neck**

***Frequency 5.68%***

Problems with the neck (fig. 7-6) were mostly attributed to the Teflon shoulder inserts when not shaped or placed properly, and was worse with donning/doffing and with shoulders abducted. There was one complaint of cervical strain due to uncomfortable head and neck positions.

***Average Severity 0.8/5 (Scale of 0 – 5)***

Causes of neck complaint are:

- Contact with Teflon inserts – 95%
- Strains – 5%



Figure 7-6. Neck.

**7.4.7 Trunk**

***Frequency 2.84%***

Problems with the trunk were all attributed to contact between components of the EMU and the affected body part. Back irritations and contusions were mostly due to hard contact with the vent tubes and plenum in the LCVGs during supine body positions (fig. 7-7). Chest and abdomen symptoms were mostly attributed to contact with the HUT, including scye joints, depending on exposure to the gravitational forces in various body positions.

***Average Severity 0.4/5 (Scale of 0 – 5)***

Causes of trunk complaint are:

- Back contact – 54%
- Chest contact – 46%



Figure 7-7. LCVGs vent tubes, back, chest.

**7.4.8 Groin**

*Frequency = 0.28%*

*Average Severity 4/5 (Scale of 0 – 5)*

The cause of groin complaint is soft goods suit contact due to fit.

**7.4.9 Head**

*Frequency = 0.28%*

*Average Severity 2/5 (Scale of 0 – 5)*

The cause of head complaint is contact with the bridge from eyeglasses. The overall severity of symptoms by location is shown in figure 7-6.

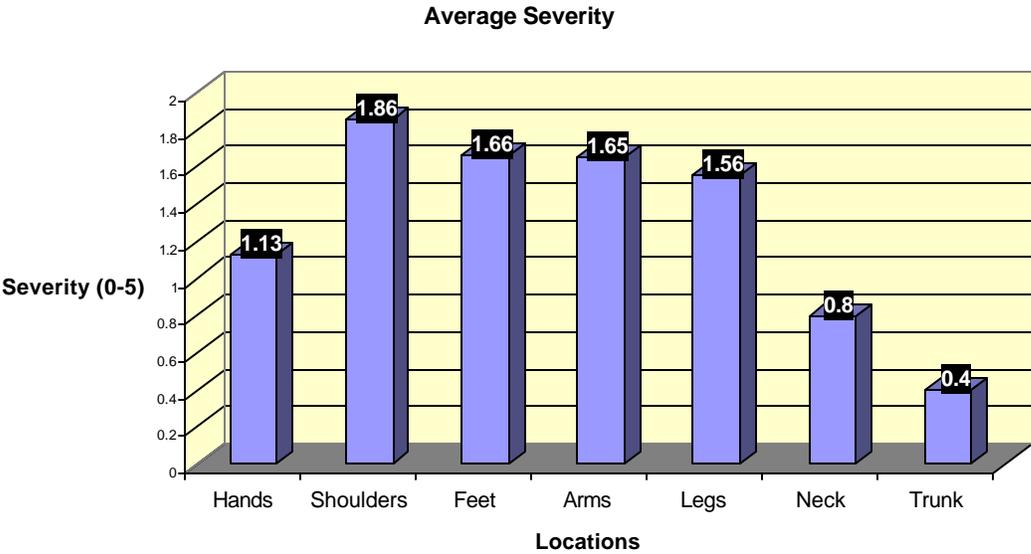


Figure 7-8. Severity of symptoms by location.

## 7.5 Effective Countermeasures by Location

### 7.5.1 Hands

The effective countermeasures for onycholysis (fingernail delamination) and fingertip pain are to provide optimal glove fit, keep the nails short, and use appropriate dressings/topical applications, including Dermabond, Tegaderm, Band-Aids, Moleskin, and tape that protects fingertips/nails and helps to keep them dry (fig. 7-9).

The effective countermeasures for contact and compression injuries are to provide optimal glove fit, arm length, and elbow alignment; have protective dressings availability, ensure hand conditioning and training for improved technique in EMU glove, and make available primary or acceptable backup gloves.



Figure 7-9. Examples of fingertip dressings.

### 7.5.2 Shoulders

The shoulder pads that are used are comfort pads #338, 335, 336, and 337 and Teflon inserts (fig. 7-10).

For the EMU shoulder harness, optimal suit fit includes unique fit adjustments for the pivoted and planar HUTs. To ensure fit, the test conductor should evaluate the anticipated frequency and duration of inverted operations and minimize such operations in the test plan. Test subjects should also be briefed and monitored when performing inverted operations or when they may be in other potentially compromising positions.

Finally, crews should received training and test planning for the use of heavy tools, on the appropriate use of diver assistance, on working inside the EMU work envelope, and on how to avoid known shoulder-stressing maneuvers.



Figure 7-10. Examples of shoulder pads, shoulder harness.

**7.5.3 Feet**

To prevent injury to the feet, avoid folds in soft goods, including socks, LCVGs, and EMU bladder folds; optimize boot fit with BSIs; wear heel pads/thermal slippers, and effectively use protective dressings such as Moleskin.

**7.5.4 Legs**

Knee contacts were generally well controlled with LCVG knee comfort pads #333, and the use of protective dressings such as Moleskin.

**7.5.5 Arms**

Elbow contacts were generally well controlled with comfort pad # 334 and with Mosite or Moleskin protective dressings.

**7.5.6 Neck**

Improve the shaping and fitting of shoulder pads with Teflon inserts. When fitting suits, consider head/neck height in the helmet in various configurations in the pool.

**7.5.7 Trunk**

To prevent injury to the trunk, ensure HUT sizing, and use stabilization back pad # 339 and Moleskin.

### **7.5.8 Groin**

To prevent injury to the groin, use a crotch pad if needed for sizing and protection.

## **8 Recommendations**

### **8.1 Hands**

To prevent injury to the hands:

- Increase hand strength and endurance using exercise prescription and follow up program coordinated by the [Astronaut Strength, Conditioning, and Rehabilitation] ASCR Team.
- Train on proper ergonomic use of hands in EMU gloves, with training provided by astronaut instructors and coordinated by the ASCR Team.
- Train astronaut on achieving the optimal glove fit and adjustments prior to NBL training.
- Train astronaut on achieving optimal elbow convolute suit fit.
- Train astronaut to understand the full range of available countermeasures.
- Continue to improve countermeasures available.

#### **8.1.1 Countermeasures development**

- Development of Moisture-Wicking Comfort Gloves – Nylon Tricot (in work by Space Suit Systems Group)
- Nail protecting/strengthening application (in work by NBL Flight Surgeon)

#### **8.1.2 Glove development**

- Keep glove position stable on wrists and hands/fingers.
- Incorporate protective finger caps.
- Improved ventilation of fingers.
- Improve palm bar position options.

### **8.2 Shoulders**

To prevent injury to the shoulders:

- Medically screen EVA candidates for a history major shoulder injuries and/or shoulder surgery. Evaluate and refer as appropriate.
- Perform upper extremity stretching, strength and conditioning exercise prescription, and follow-up program coordinated by the ASCR Team.
- Conduct extensive astronaut training on optimal suit fit, donning/doffing, and EMU work techniques, including body stabilization especially when using heavy and torque tools.

- Provide extensive astronaut training on optimal suit fit and the effective use of all available countermeasures.
- Consider reintroducing the EMU shoulder harness (redesign and additional testing by Space Suit Systems Group for crew consensus).
- Contemplate adding “memory foam” as a shoulder pad option.
- Improve heavy tool buoyancy (lighter material design, weigh out, diver assistance).
- Plan training tasks to avoid provocative body positions and stressors as much as possible; e.g., establish and maintain a good weigh out, limit heads-down operations, and avoid shoulder overreaching outside a safe work envelope.
- Build in planned and requested diver assistance when appropriate.

### **8.2.1 Suit development**

- Improve suit shoulder joint, biomechanics, and safe shoulder work envelope.
- Improve fit options for smaller and larger astronauts.
- Reduce shoulder stress with ingress/egress.
- Incorporate design modification requirements to fully consider significant differences between the training environment at the NBL and the flight environment.

### **8.3 Feet**

Optimize effective countermeasures to prevent injury to the feet.

#### **8.3.1 Boot insert development**

Provide an accommodating orthotic for enhanced fit, protection of dorsal feet/toes, and appropriate arch support. Certify for flight as well as for training. If necessary, improve boot-sizing options to consider the volume required for an accommodating orthotic.

### **8.4 Legs (Knees)**

- Provide astronaut training to optimize suit fit; align function of knee joint with convolute position.
- Offer Astronaut training to avoid knee-straining maneuvers, especially in donning PFRs/APFRs.

### **8.5 Arms (Elbows)**

- Provide astronaut training to optimize suit fit; align function of elbow joint with the convolute position.

- Develop astronaut training to optimize the use of countermeasures, including available padding (Moleskin or LCVG padding).
- Ensure astronaut training and conditioning of forearms and wrists.
- Avoid elbow-stressing maneuvers, especially with heavy tools and torque tools.

## **8.6 Neck**

- Properly shape and position Teflon shoulder pad inserts.
- Ensure neck conditioning exercises are supervised by the ASCR Team.
- Perform suit fit to allow full head extension into helmet without shoulder impingement.
- Avoid neck-stressing head positions.

## **8.7 Trunk (Back, Chest, and Abdomen)**

- Optimize HUT fit.
- Make maximum use of available countermeasures such as padding and Moleskin.

### **8.7.1 LCVG development**

Build in padding to reduce hard contact with the vent tube/plenum system.

## **9 Conclusions and Recommendations**

### **9.1 Summary**

- Approximately half of EMU NBL training events were symptom-free and were characterized by no complaints or medical findings. Although after many of these training events requests were made for changes in suit sizing or countermeasures, there was no medical basis for these requests.
- Most reported symptoms were minor and self-limited. Of the reported suit symptoms, the vast majority consisted of areas of localized discomfort that resolved rapidly and without injury.
- From a medical perspective the areas in which the most significant, frequent, and persistent problems occurred were in the hands, shoulders, and feet. Many of these problems have improved with increased use of available countermeasures. However, a stable frequency of fingernail delamination, shoulder injuries, and foot pain persists. These issues especially require ongoing attention and the application of future resources.
- The process of optimizing the use of appropriate countermeasures is effective in reducing or eliminating many EMU suit symptom complaints. This study process

has brought into focus the nature and extent of many common suit-related symptoms experienced by astronauts in NBL training. Communication and cooperation among the astronauts, NBL flight surgeons, and suit engineers has further improved the effective use of available countermeasures. That and the efforts to develop improved countermeasure options have already begun to significantly improve astronaut health and performance.

## 9.2 The Future

- I suggest that the EMU Medical Working Group review each of the specific recommendations listed in Section 8, agree on appropriate actions, and present those actions to each respective Directorate.
- Continue surveillance by the NBL flight surgeons to follow significant EMU medical issues, including trends and additional recommendations that may be developed. Report results to the EMU Medical Working Group on a quarterly basis for now.
- Injury prevention should include specific flight medicine screening of astronauts scheduled for EMU training to address any history of preexisting injuries and surgery that are likely to be aggravated by EMU NBL training. This can be accomplished at the time of the astronaut's annual physical examination. Appropriate referrals to medical specialists and the ASCR Team can then be made. All astronauts in EMU training should be strongly encouraged to seek ASCR evaluation and recommendations for individualized exercise programs to best prepare them for the rigors of NBL EMU training and, ultimately, EVA.
- The NBL flight surgeons will continue to provide immediate recognition of early injuries and appropriate referral to flight medicine/crew surgeons for effective treatment and follow up.
- Improve astronaut training and test planning to avoid situations in which injuries have been known to occur. Optimize astronaut monitoring during potentially stress-provoking test events and discontinue provocative maneuvers when warranted.
- Early and ongoing astronaut training is needed to achieve a better understanding of unique EMU ergonomic design characteristics, including ranges of motion, reach, body positions, and resistance to effort. Training should also include a complete understanding and the effective use of all available countermeasures so they may be requested as required. Focus should be placed on differences in EMU human factors between NBL training and space flight.
- Likewise, improved early and ongoing astronaut training is needed to achieve a better understanding of the ergonomics of the use of EMU heavy tools in the NBL. This training should emphasize heavy tool handling/use techniques, body positioning, and body stabilization—without introducing “negative training.” Appropriate requests for diver assistance should be incorporated in astronaut training and test planning. Focus should

also be placed on the differences in heavy tools human factors between NBL training and space flight.

- Optimize current EMU and heavy tools. To provide needed short-term improvements in EMU Class III hardware, I suggest that a parallel two-track approach be taken to improve current design human factors and medical issues: (1) to modify currently certified Class III equipment, and (2) to include recommended design improvements in the future development of a new EVA suit.
  1. Write glove modifications and future development requirements so as to consider the recommendations made in Section 8.1.
  2. Write EMU modifications and future design requirements in light of the recommendations made in Sections 8.2 and 8.3.
  3. Continue requirements to develop EMU heavy tools for improved buoyancy and ease of use in the NBL training environment.
- Develop the next-generation spacesuit and tools incorporating lessons learned from this study and future experience.
- Ensure future spacesuit design requirements incorporate the unique demands of NBL training as well as of the space flight environments.

### **9.3 Final Comments**

Following approval by its sponsor, this study will be disseminated to all interested parties in the Space and Life Sciences Division including the Human Test Support Group, Space Medicine and Health Care Systems, and the Astronaut Strength Conditioning and Rehabilitation Team. Using these study findings, appropriate recommendations should be made to all interested Directories and Offices at JSC including Flight Crew Operations, Mission Operations, the EVA Office, Engineering, and Safety and Mission Assurance. Results and recommendations are being disseminated in written and briefing formats. Acceptance and implementation of these recommendations can be expected to result in better control of identified mechanisms of injury, improved astronaut health, and an enhanced quality of NBL EVA training.

#### **9.3.1 NASA data access plan for future investigators**

This database is listed in the Catalog of Medical Data Repositories of the Space Medicine and Health Care Systems office of Medical Informatics. The principal investigator retains control of access to data.

The Catalog of Medical Data Repositories entry is listed as follows:

EMU SUIT SYMPTOMS DATABASE  
THIS IS AN ASTRONAUT SPECIFIC DATABASE OF PAIN AND / OR PARESTHESIA  
SYMPTOMS, OBJECTIVE SIGNS AND ATTRIBUTABLE CAUSES. DATA COLLECTED

PROSPECTIVELY BY AN NBL FLIGHT SURGEON AT THE CONCLUSION OF NBL TRAINING RUNS, USING A QUESTIONNAIRE FORMAT.

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13. ABSTRACT (Maximum 200 words)  The purpose of this study was to characterize the symptoms and injuries experienced by NASA astronauts during extravehicular activity (space walk) spacesuit training at the Neutral Buoyancy Laboratory at Ellington Field, Houston, Texas. We identified the frequency and incidence rates of symptoms by each general body location and characterized mechanisms of injury and effective countermeasures. Based on these findings a comprehensive list of recommendations was made to improve training, test preparation, and current spacesuit components, and to design the next -generation spacesuit. At completion of each test event a comprehensive questionnaire was produced that documented suit symptom comments, identified mechanisms of injury, and recommended countermeasures. As we completed our study we found that most extravehicular mobility unit suit symptoms were mild, self-limited, and controlled by available countermeasures. Some symptoms represented the potential for significant injury with short- and long-term consequences regarding astronaut health and interference with mission objectives. The location of symptoms and injuries that were most clinically significant was in the hands, shoulders, and feet. Correction of suit symptoms issues will require a multidisciplinary approach to improve prevention, early medical intervention, astronaut training, test planning, and suit engineering.				
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